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Performance Reliability and Durability of Future High-Power Pulser-Switch Components for the Electric Gun

by C. W. Hubbard, M. W. Cole, J. D. Demaree, C. G. Fountzoulas, D. Harris, A. Natarajan, P. Searson, R. A. Miller, and D. Zhu

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Abstract

This study developed and performed laboratory experiments that mimic the acute thermal cycling inflicted on device structures during high-power switching for use in future electromagnetic (EM)-gun systems. Ni contacts to n-SiC were the device components selected for cyclic thermal testing. Modifications of the Ni-SiC materials properties in response to cyclic thermal fatigue were quantitatively assessed via Rutherford backscattering spectrometry (RBS), scanning electron microscopy (SEM), atomic force microscopy (AFM), surface profilometry, transmission electron microscopy (TEM), and nanoindentation testing. Decreases in nanohardness, elastic modulus and surface roughness were observed in response to thermal fatigue. No compositional modifications were observed at the metal-semiconductor interface. Our results demonstrated that the majority of the material changes were initiated after the first thermal pulse and that the effects of subsequent thermal cycling (up to 10 pulses) were negligible. The stability of the metal-semiconductor interface after exposure to repeated pulsed thermal cycling lends support for the utilization of Ni as a contact metallization for high-power pulsed-switching applications.

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1. Introduction

Future U.S. Army tank requirements warrant reductions in volume and weight in order to promote vehicle airlift mobility deployment. To satisfy this demand, tank components must undergo weight and volume reductions, while maintaining performance specifications. The electromagnetic (EM) gun, specifically the EM-gun pulser (high-power switch system), is one of the critical components that must be addressed. Switches can be plasma type or solid state. The feasibility of using solid-state Si power thyristors for EM-gun pulsers is well established (Pasture et al. 1993; Spalm et al. 1993). In terms of fielding an electric gun, solid-state switches offer significant performance advantages over the traditional plasma-type switches, namely, high repetition rate, long lifetime, low maintenance, and high reliability. Si-based high-power switches afford a major limitation, in that a large number of Si devices would be needed to achieve the required gun performance. This large number of Si devices would make the pulser nonoptimal in terms of size and weight. However, the superior material properties of SiC over Si advocate increased device power density and di/dt capabilities; thus, solid-state SiC switches offer a potential 60% reduction in both volume and weight (Burke et al. 1997). In other words, compared with Si, SiC high-power switches would operate over higher voltage and temperature ranges, with superior switching characteristics and smaller die sizes. Thus, SiC allows superior performance while addressing the need for both volume and weight reductions.

If SiC is to be pursued for EM-gun pulsers, the issues of thermal stability, durability, and reliability (to ensure extended high-temperature operation at high voltages) of the SiC device components that compose these high-power switching devices must be addressed. In the high-temperature, high-current-density, and short-pulse operating regime required for electric guns, mechanical stresses related to thermal expansion are a major limiting mechanism. Thus, durability and reliability of device components under cyclic thermal loading are crucial factors that strongly influence EM-gun performance and lifetime. High-power switches (thyristors) are composed of several device structures. For the purpose of this study, a metal contact to n-type 4H SiC structure was selected for testing. This selection was based on the premise that contacts are a fundamental component of all high-power devices and extended high-temperature operation

that may potentially cause chemical degradation of the SiC-contact interface via initiation-propagation of material defects and indiffusion of the contact metallization into the SiC, thereby restricting the device's functional lifetime. Thus, the ohmic contact-SiC structure may be tagged as a potential performance-limiting device component for the electric gun pulsers.

In this work, we investigate the durability, thermal stability, and reliability of metal contacts to n-type 4H-SiC as a function of acute cyclic thermal loading. Typically, thermal stability has been assessed via static loading, but for high-power applications, such as the EM gun, durability/stability under acute thermal cycling is critical. A fair amount of work has focused on formation of ohmic contacts to SiC; however, in spite of the importance of contact thermal durability/stability, the amount of work reported in this area is very limited. A number of different metals have been proposed as suitable ohmic contacts to n-SiC. Specifically, metals such as Ni, Al/Ni/Al, Cr, Al, Au-Ta, $TaSi_2$, W, Ta, Ti, Ti/Au, $TiSi_2$, Co, and WSi have been studied, with the Ni-based metallization systems suggested as superior candidates due to their low ρ_C (~10^{-6} Ω-cm^2) (Hallin et al. 1997; Crofton et al. 1995). Based on this information, we have selected Ni as the contact metallization for cyclic thermal fatigue testing. The Ni metallization was deposited via electron-beam (e-beam) evaporation. The changes in the material properties of the contact to SiC as a function of acute cycled thermal fatigue were evaluated via optical and scanning electron microscopy (SEM), Rutherford backscattering spectroscopy (RBS), atomic force microscopy (AFM), profilometry, transmission electron microscopy (TEM), and nanoindentation.

2. Experimental

Two hundred nanometers of Ni were deposited on 4H n-type SiC substrates purchased from CREE Research. The SiC substrates were nonresearch-grade substrates with a micropipe density of greater than 100 cm^{-2}. The substrates were Si faced, and the donor density was 2.0×10^{19} cm^{-3}. Prior to the metal deposition, the wafers were cleaned in warm electronic-grade trichoroethane (TCA), boiling acetone, and methanol, followed by a rinse in deionized water. The Ni deposition was accomplished via e-beam evaporation. The e-beam evaporation of Ni on

SiC took place with a base pressure of 5×10^{-7} torr. The e-beam deposited Ni on SiC samples was annealed at 950° C for 5 min in an N_2 ambient in order to produce ohmic behavior. Cyclic thermal fatigue tests were conducted using a 10.6-μm infrared (IR)-pulsed CO_2 laser. Since the switch module requirements for EM-gun performance specifies a short pulse width, the laser was designed to cycle, or pulse, to mimic switch module requirements for EM gun. Specifically, each cycle consisted of a 3-s heating interval followed by a 60-s cooling interval. Laser power levels were tailored to maintain a temperature of 650° C for 1 and 10 consecutive cycles. Temperature verification was obtained with the aid of both a thermocouple and pyrometer.

Materials and electrical characterization were performed on all samples. Current-voltage measurements were performed on the as-deposited, annealed, and thermally fatigued Ni-SiC samples. The ohmic contact to the backside of the SiC wafers was made by using In-Ga eutectic. The electrical measurements were internally consistent and were used solely to assess the electrical changes resulting from thermal fatigue relative to the nonfatigued sample. All samples were analyzed for surface morphology modification via AFM and surface profilometry. A Topometrix Discoverer Scanning Probe system was used to obtain the AFM data, and the profilometry measurements were obtained via a Tencore P-2 low-scan profiler. Surface inspection of the metallized SiC surfaces was accomplished using an Amray 1830 SEM, with x-ray elemental mapping capabilities via a Kevex Sigma 2 energy-dispersive spectroscopy (EDS) system. Elemental diffusion and phase formation were tracked using RBS. RBS measurements were obtained on a National Electronics Corp. 55DH-2 Accelerator using 2-MeV He^+ ions with a scattering angle of 170° and a solid angle of 5.5 msr. Experiments were performed at a tilt angle of 10° away from the detector in IBM geometry (beam, surface normal, and detected beam are coplanar). Simulations were produced using the computer code RUMP. The structural durability of the thin-film metallization on SiC was evaluated via nanoindentation testing. The nanoindentation measurements were made using a Nano Instruments XP nanoindenter, with a Berkovich 3-sided pyramid diamond indenter with controlled penetration depths of 300 nm. The instrument allowed an indenter penetration vs. force curve to be determined allowing the determination of both nanohardness and the effective elastic modulus from the slope of the

hysteresis curve. Microstructural analyses were obtained via cross-sectional TEM using a JEOL 3010 STEM operated at 300 keV.

3. Results and Discussion

The current-voltage (I-V) characteristics of the e-beam as-deposited Ni film displayed rectifying behavior. The RBS analysis (Figure 1) revealed no reaction between the Ni and SiC substrate and showed no evidence of an interfacial oxide upon Ni deposition. The I-V curve for the annealed e-beam deposited Ni on SiC possessed near-linear characteristics and was symmetric with reversal of the voltage polarity; however, the resistance was not negligible. The electrical measurements suggest that this is not an optimized contact. RBS analysis of the annealed e-beam deposited Ni on SiC (Figure 2) showed a thin layer of NiO present at the contacts surface and Ni silicide formation adjacent to the SiC. The contact-SiC interface was not abrupt, and thickness of the contact increased from 200 nm to 400 nm as a result of interfacial reactions during annealing.

This large increase in contact thickness has been documented in the literature for Ni contacts on SiC (Hallin et al. 1997). The RBS analysis also revealed evidence of C incorporation into the film during the silicide formation. According to Hallin et al. (1997), Ni silicide, with incorporated C, serves to degrade the ohmic contact. Thus, the presence of C in the silicide layer may explain the high resistivity of this contact. It has also been suggested that excess C at the metal-SiC interface contributes to poor film adhesion and delamination (Chaudhrey, Berry, and Zeller 1990). The nonabrupt interface characteristics noted in the annealed e-beam deposited samples have been documented by others for Ni-based contacts to SiC (Hallin et al. 1997; Chaudhrey, Berry, and Zeller 1990). For Ni contacts to SiC, formation of Ni silicides upon annealing appears to be a requirement for ohmic behavior. The critical step in silicide formation requires the continual supply of Si atoms through breaking bonds in the substrate. The Si-C bonds can be broken in several ways; sufficient thermal energy to break the SiC bonds (high temperatures) and/or rapid interstitial migration of the metal through the SiC lattice, which assists bond breaking and aids silicide formation. Since our samples were annealed at a fairly

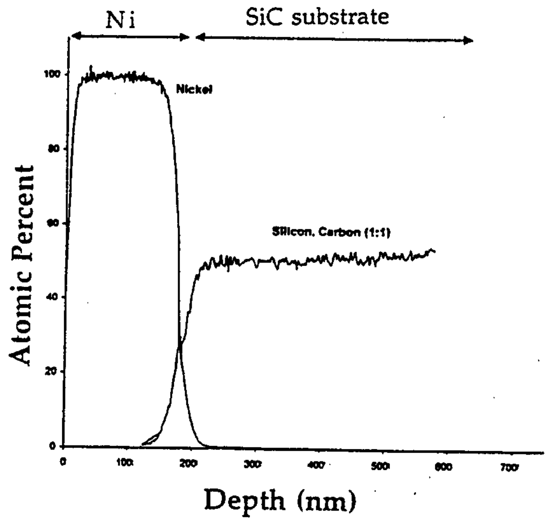


Figure 1. RBS Depth Profile for the E-Beam As-Deposited Ni on SiC.

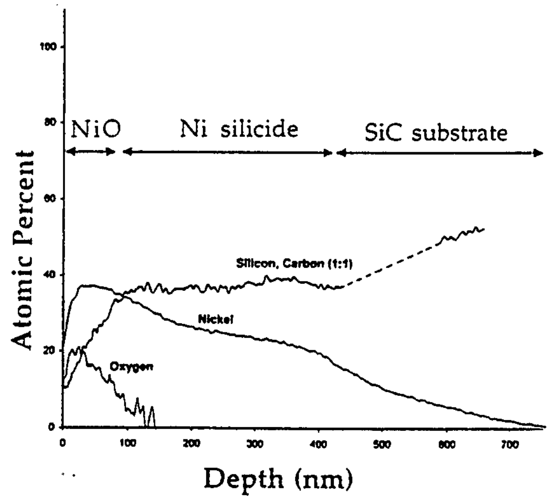
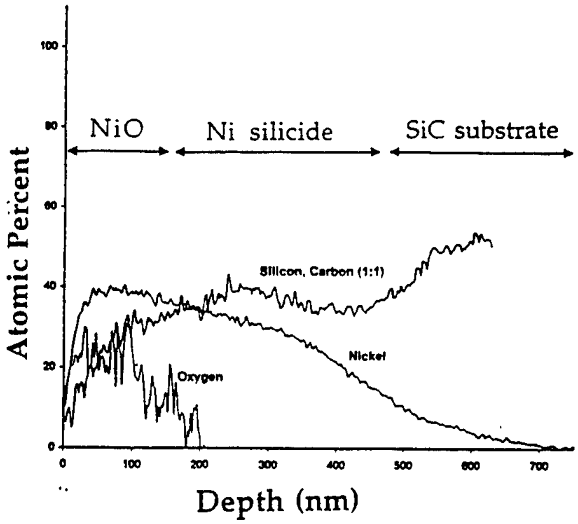


Figure 2. RBS Depth Profile for Annealed Ni Contact to SiC.

high temperature and Ni is very small (0.69 Å ionic radius) compared to that of SiC (2.71 Å) and C (2.60 Å), both of these mechanisms may have contributed to the formation of the silicide phase detected by RBS.

Thermal fatigue experiments were performed on the annealed Ni-SiC samples. RBS analyses of the 10-cycle thermal fatigued sample (Figure 3) revealed no compositional changes at the metal semiconductor interface. However, oxygen appears to have penetrated a bit deeper into the sample. This oxygen penetration may have resulted from nanocracks in response to the thermal shock. It must be kept in mind that the interfacial properties of the metal contact to SiC strongly influence electrical performance. The fact that the metal-semiconductor interfacial region remained compositionally unchanged lends support to the integrity of this contact in response to pulsed thermal fatigue.

Optical and SEM analysis showed that the surfaces of the as-deposited e-beam evaporated Ni thin film on SiC was smooth and mirror-like in appearance. However, after annealing at 950° C, the surface changed drastically. The mirror-like metallic luster changed to a lusterless dull gray color, and the film was no longer smooth. The surface morphological changes were quantified via profilometry and AFM analyses and are displayed in Figure 4. The magnitude of the profilometry data is larger than that of the AFM data, but the general trends parallel one another.



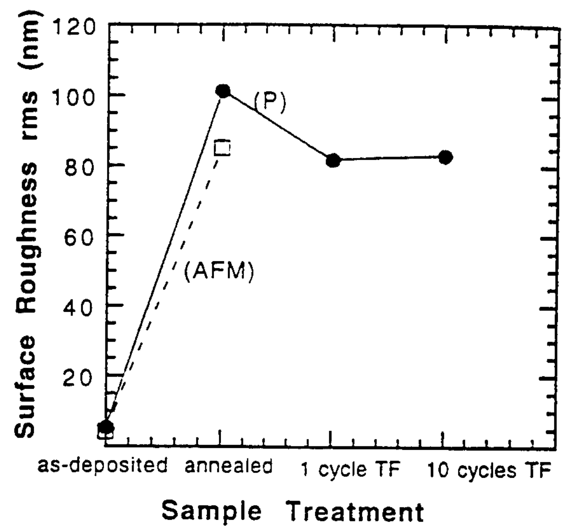


Figure 3. RBS Depth Profile for the Annealed Ni Contact to SiC After 10 Cycles of Thermal Fatigue.

Figure 4. Surface Roughness. ATM and Profilometry (P) Data Parallel to One Another.

It is evident from Figure 4 that annealing augmented the surface roughness of the metal film. Specifically, the surface roughness increased by an order of magnitude. This is not surprising since surface roughness has been commonly observed during silicide formation in Si technology. The film's surface remained lusterless after the thermal fatigue; however, the surface became smoother. This surface smoothening occurred during the first cycle of the pulsed thermal fatigue and maintained at steady state through the 10th cycle; that is, the rms roughness value remained constant throughout the duration of the thermal cycling. We suggest that the initial thermal shock of the first laser pulse caused the removal of a thin layer of loosely bound particles from the film's surface, which resulted in a lower rms roughness value. The fact that the film did not delaminate and that the rms roughness value remained constant throughout the thermal cycling bodes well for the film's strong adhesion and cohesion properties. Figure 5 displays SEM micrographs of the Ni film as a function of sample treatment. The SEM micrographs clearly show the surface smoothening resultant from the thermal fatigue.

Mechanical properties, such as nanohardness and Young's modulus, were used to assess the changes in the physical durability of the metal-SiC component in response to thermal fatigue. Simply defined, the hardness of a thin film is the resistance of the film to penetration of its

(a) After 1 Cycle of Thermal Fatigue. **(b) After 10 Cycles of Thermal Fatigue.**

Figure 5. Surface Morphology.

surface (i.e., resistance to local plastic deformation [Nix 1989]). Hardness is a complex macroscopic property related to the strength of interatomic forces and depends on several variables. In this study, nanohardness was used as an indication or quantitative measure of the film's physical durability. It must be kept in mind that there is a strong relationship between a film's microstructure and its mechanical properties (Nix 1989). Grain size, area, and boundary structure; film composition (new-phase formation); impurities; defects; and film texture all influence and/or control the nanohardness/durability of thin films. As a rule, the larger grain sizes augment a film's hardness and porosity and fine nanocracks diminish hardness. Films grown by physical vapor deposition (PVD) methods, such as e-beam evaporation, usually display a preferred orientation with low-index planes lying parallel to the substrate (textured film), which results in elevated hardness values compared to the same film with randomly oriented planes.

The magnitude of Young's (elastic) modulus is determined by the strength of the atomic bonds in the film. The stronger the atomic bonding, the greater the stress required to increase the interatomic spacing and, thus, the larger the value of the modulus of elasticity and the more durable the film (Nix 1989). Like hardness, the modulus is a macroscopic property that depends on many different variables at the atomic level. The bond strength (the values of Young's modulus) varies with crystallographic direction. Therefore, in a polycrystalline film, a preferred orientation or texture will influence the magnitude of the Young's modulus. Modification of the film's chemical composition also influences the modulus value since the various phases are

composed of different atomic species with different bond strengths. Thus, changes in the film's mircrostructure and composition will be reflected in the values of the film's nanohardness and elastic modulus.

Figure 6 displays the nanohardness and Young's modulus values for the as-deposited, annealed, and thermal-fatigued contact metallization on SiC. The nanohardness and modulus values change significantly with sample treatment, showing a decrease in magnitude in response to annealing and cyclic thermal fatigue. The largest change in both the hardness and modulus occurs after the first thermal pulse. Additional thermal cycling caused negligible changes in these properties. TEM analysis revealed that the as-deposited Ni on SiC consisted of a small-grained (<200-Å diameter) equiaxed polycrystalline structure. This correlates well with the zone model classification scheme developed by Hentzall, Grovenor, and Smith (1984) for thin evaporated films. TEM analysis of the annealed Ni-SiC is currently in progress. However, as mentioned earlier, the RBS results demonstrated that annealing promoted both compositional and structural changes in the contact. This concurs with the results of other researchers (Crofton et al. 1995; Chaudhry, Berry, and Zeller 1990). It has been demonstrated that Ni silicide formation is often accompanied by void formation. It is not unreasonable to postulate that a similar film microstructure exists in our annealed films. The annealed Ni film's compositional changes, combined with the suspected increase in film porosity, support the observed decrease in both nanohardness and elastic modulus. Further depression of these values, after exposure to one cycle of thermal fatigue, is most likely due to the promotion of defects and thermally induced nanofractures within the contact film. The fact that the hardness and modulus do not change significantly after 10 cycles suggests that multiple or repeated thermal cycling has a negligible affect on the film's durability. This speaks well for the reliability of the Ni contact's endurment to repeated pulsed thermal cycles.

The I-V curve for the thermal fatigued contact on SiC looked quite similar to that of the unfatigued sample (i.e., possessing quasi-linear characteristics and symmetry with reversal of the voltage polarity). Although this was not an optimized contact, the fact that the thermal fatigue did not significantly degrade the I-V curve speaks well for the integrity of this contact in response to cyclic thermal fatigue.

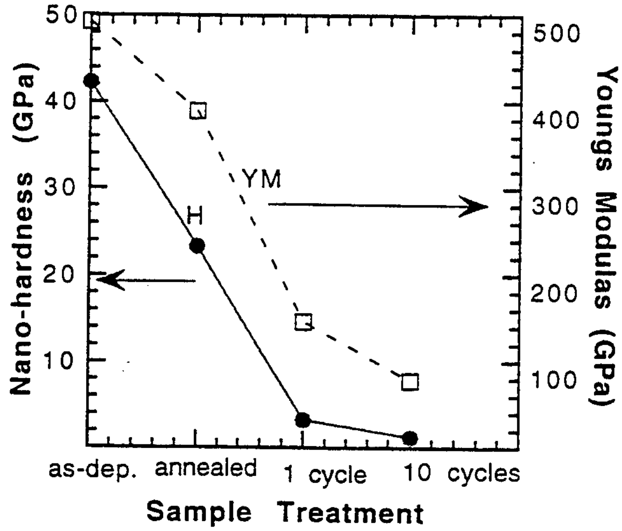


Figure 6. Nanohardness and Young's Modulus Values as a Function of Sample Treatment.

Future work will focus on repeating the thermal fatigue experiments using Ni and other metallizations on higher quality n-type SiC (lower defect densities). The influence of the high defect density SiC needs to be removed in order to fully test the thermal stability, durability, and reliability of various contact metallizations in response to cyclic thermal fatigue. Metallizations to p-SiC will also be addressed. In addition, SiC epilayers will be used such that measurements of specific contact resistance can be obtained.

4. Summary

In summary, we have developed and performed laboratory experiments that mimic the acute thermal cycling inflicted on device structures during high-power switching in the EM gun. Evaluation of the material changes incurred by the Ni contacts to SiC in response to acute cyclic thermal fatigue has been investigated. Pulsed thermal fatigue caused microstructural alterations that were directly reflected in the contacts mechanical or durability properties. Our results demonstrated that most of the material changes occurred in response to the first pulse of the cycling and that further cycling (up to 10 pulses) inflicted negligible changes in the contact-SiC durability and material properties. The stability of the metal-semiconductor interface after acute thermal cycling lends support for the utilization of Ni as a contact metallization for high-power pulsed-switching applications.

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